HYDRODYNAMICS OF DOWNSTREAM POINTED GUIDEVANES

A CASE STUDY OF THE

HESS CREEK MEANDER BEND REALIGNMENT

By

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A

THESIS

Presented to the Faculty

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By

Alexandre Lai

Fairbanks, Alaska

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Abstract

The hydrodynamics of downstream pointed guidevanes installed to realign an eroding meander bend upstream of the Trans- Alaska Pipeline bridge is studied. The bridge is located at Hess Creek, 137 km north of Fairbanks, Alaska. Effect of the downstream pointed vanes on bed form, erosion, longitudinal and transverse slopes, three dimensional velocity profiles, flow patterns, and other hydraulic parameters for high and low flows are compared and analyzed. Six years after installation of the vanes the realigned thalweg remains in its original design location. The longitudinal bed profile changed from a dominant continuous pool typical of natural meander bends on gravel stream beds to a series of pool riffles. However, there is minimal change in maximum scour depth between post and pre installation of the vanes. Secondary or transverse current patterns which cause scour or erosion on the outer bank are severely disrupted due to interference caused by the vanes. There is a consistent weak counter current in reaches between the vane stems due to flow separation caused by expansion of flow area. This condition was more dominant during low flows when the vanes were not completely submerged. From the tip of the vanes to the inner bank a more dominant transverse and streamwise current was measured. Location of the original eroding outer bank remains unchanged since installation of the vanes. This indicates that the vanes have to this point effectively realigned the meander bend and arrested additional lateral movement of the meander.

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Acknowledgements

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To my family Lee, Jorge, and Manuel thank you for staying with me on this odyssey. We have moored, rested, and taken refuge on many isles and nobody fears the one eyed giant anymore. As the boys like to say, 'all for one and one for all.'

Chapter 1 Introduction

Rivers are dynamic systems with interdependent variables that change in plan, profile, and form over time. When men build infrastructure such as bridges that cross riverine systems the channel features at the time of construction such as pattern and profile are a snapshot in time. It is a still frame of a reach which is linked to the entire river continuum constantly adjusting itself to towards a state of equilibrium.

Hess Creek is located 137 km north of Fairbanks, Alaska at Dalton Highway milepost 24 and is approximately 51 km south of the Yukon River. The Trans-Alaska Pipeline Bridge crosses Hess Creek at pipeline milepost 375 (Alyeska Pipeline Service Company 1973) on its 1285 km journey from the Beaufort Sea at Deadhorse, Alaska to the port of Valdez. The pipeline bridge crossing Hess Creek is 40 m wide and is supported by a 55 m single span steel plate girder bridge. It has a drainage basin of 1310 km^2 and the bankfull discharge is 96 m^3/s, based on a flood frequency analysis of a USGS gauge station at Hess Creek located downstream of the study reach. The area is underlain with discontinuous permafrost with a typical floodplain soil profile consisting of an organic layer on the surface followed by silts, and alluvial gravels and sands down to bedrock.

At the time of construction in 1976, the pipeline crossing appeared to be a stable reach with well-vegetated banks and few signs of bank erosion. A decade later, bank erosion upstream of the pipeline bridge was observed. The erosion continued upstream of the bridge abutment and accelerated in the early years of 2000. Continued lateral erosion resulted in formation of a meander bend upstream of the bridge in what used to be a relatively straight reach at the time of construction. This resulted in a misalignment at the bridge between the upstream and downstream reaches of the creek. With continuing lateral stream migration there was increased risk that the stream would outflank the bridge abutment in a major flood event.

There were diverse needs and expectations from various stakeholders. They were protection of the pipeline infrastructure, aquatic habitat preservation, protection of an ecologically delicate area, and navigation for subsistence and/or recreational purposes.

To meet these stakeholder needs an innovative approach to traditional river engineering was used to achieve the goals. Downstream pointed re-directive rock vanes were designed and built to realign the meander bend upstream of the pipeline crossing. This is the first time the design concept was implemented in Alaska. The present study assesses the effectiveness of these re-directive vanes. Hydraulic and geomorphic parameters such as flow patterns, velocities, gradients, depositional and scour patterns are investigated. Pre and post construction geodetic monitoring surveys were performed on the study site. Three dimensional velocity measurements were taken on the study reach during high and low flow conditions to analyze flow patterns, secondary velocities, and other hydraulic parameters such as Manning's roughness coefficient.

1.1 Objective

The objectives of this thesis are the following:

- To study the influence of downstream pointed rock vanes on channel hydraulics such as, velocities, stream gradient, and flow patterns.
- Verify if there are hydraulic differences between low and high flow conditions.
- Study the impact of the vanes on geomorphic features such as thalweg, bedform, and scour.
- Evaluate the overall effectiveness of the rock vanes as a tool to arrest lateral bank migration and realign meander bends.

1.2 Outline

The text is presented in chapter 2, which corresponds to a manuscript submitted for publication in the Journal of Hydraulic Engineering. Chapter 3 presents the overall conclusions and suggestions for future work.

1.3 References

Alyeska Pipeline Service Company. 1973. *Summary Report River and Floodplain Design Criteria for the Trans Alaska Pipeline System*.

Chapter 2 Hydrodynamics of Downstream Pointed Guidevanes A Case Study of the Hess Creek Meander Bend Realignment[1]

Abstract:

Hydraulics and effectiveness of downstream pointed guidevanes used to realign a meander with a pipeline bridge are investigated. Field measurements at high and low flows were made and analyzed for velocities, flow patterns, stream gradient, super elevation, and bed topography. After six seasons of monitoring the thalweg remained in its design location, the bedform changed from a single pool along the meander bend to a series of pool riffles and the outer bank stopped eroding. There is minimal change in maximum scour depth between post and pre installation of the vanes. Vanes installed along the outer bank severely disrupt the natural spiral flow patterns in a river bend due to interference caused by the vanes. Boundary shear stresses are transferred from the outer bank toe towards the tip of the vanes. A consistent weak counter current is present in reaches between vane tip and the outer bank. It is the result of flow separation caused by expansion of flow area between vane stems. This condition was more dominant during low flows when the vanes were not completely submerged. From the tip of the vanes to the inner bank a more dominant transverse and streamwise current was measured. The thalweg is found in this section. Location of the original eroding outer bank remains unchanged since installation of the vanes. This indicates that the vanes have to this point effectively realigned the meander bend and arrested additional lateral movement of the meander.

2.1 Introduction

Innovative and experimental techniques to control bank erosion at meander bends are being used more frequently to satisfy diverse stakeholder demands (Woolsey et al 2007).

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[1] This chapter was submitted to the Journal of Hydraulic Engineering for publication

In the case of Hess Creek Trans Alaska Pipeline crossing located 137 km north of Fairbanks, Alaska, USA, there were diverse needs and expectations from various stakeholders.

To address these diverse needs various types of instream structures such as bendway weirs (Derrick 1996), cross vanes and J hooks (Rosgen 2001), riffles (Newbury et al. 1997), and engineered log jams (Abbe et al. 2003), have been studied and built at other sites across North America. Recently Bhuiyan et al. (2010) did experimental studies on the effectiveness of bank-attached vanes for bank erosion control and restoration. Jia et al. (2009) performed numerical studies on flows affected by bendway weirs installed on the Mississippi River. However there are very few studies or literature on the use and effectiveness of downstream pointed re-directive vanes to control erosion and restore streams. At Hess Creek the design concept was implemented in Alaska for the first time. The stakeholder expectations at Hess Creek were protection of the pipeline infrastructure, aquatic habitat preservation, protection of an ecologically delicate area, and navigation for subsistence and/or recreational purposes. The design philosophy for this project was to install a system that would provide maximum elasticity to the restored reach and still protect the pipeline bridge crossing for the next forty years. It required a design that would accommodate lateral and vertical stream mobility in response to hydraulic and sediment changes in the watershed. These changes may be triggered from high spring breakup or summer flood events, wildfires, etc.

This study investigates the effectiveness of downstream pointed re-directive vane structures. Principal guidelines for the design were from an approach applied by the Rural Water Commission of Victoria in Australia (Standing Committee on Rivers and Catchments 1991). The vanes were used to re-align a laterally migrating meander bend upstream of a pipeline bridge. Infrastructure such as pipelines and highways that traverse large geographic distances inevitably must cross rivers along their paths. The stream form at the location selected for the crossing may appear stable at the time of design and construction. But rivers are dynamic process based systems that adjust over time to changes in the watershed such as hydrological, geomorphic, land use practices, and other man made or naturally induced events. These time dependent variables can significantly alter the morphology of a river crossing years after its installation.

The Trans-Alaska Pipeline Bridge crosses Hess Creek (Latitude 69.968611 north, Longitude 148.715833 west) at pipeline milepost 375 on its 1285 km journey from the Beaufort Sea at Deadhorse, Alaska to the port of Valdez. At the time of construction in 1976, the pipeline crossing was a stable reach with well-vegetated banks and few signs of bank erosion (Fig. 2.1).

Figure 2.1 Photograph of Pipeline bridge crossing in 1977 shortly after installation

Two decades later, considerable bank erosion upstream of the pipeline bridge was observed. Continued lateral movement due to erosion resulted in formation of a meander bend upstream of the bridge in what used to be a relatively straight reach at the time of construction. This resulted in a bridge misalignment between its upstream and downstream reaches. There was a risk that in a flood event the stream could outflank the bridge abutment (Fig. 2.2).

Figure 2.2 Photograph of Hess Creek, 2001 lateral bank migration

Downstream pointed re-directive rock vanes were designed and built to realign the meander bend upstream of the Pipeline crossing. Hydraulic and geomorphic parameters such as flow patterns, velocities, gradients, depositional and scour patterns are investigated. Pre and post construction geodetic monitoring surveys were performed on the study site. Three dimensional velocity measurements were taken on the study reach during high and low flow conditions to analyze flow patterns, secondary velocities, and hydraulic gradients.

2.2 Methodology

A pre-construction topographic survey to collect baseline data was done in November 2004. The survey captured physical features such as, channel cross sections, thalweg, inner and outer banks positions, and point bar elevations (Fig. 2.3).

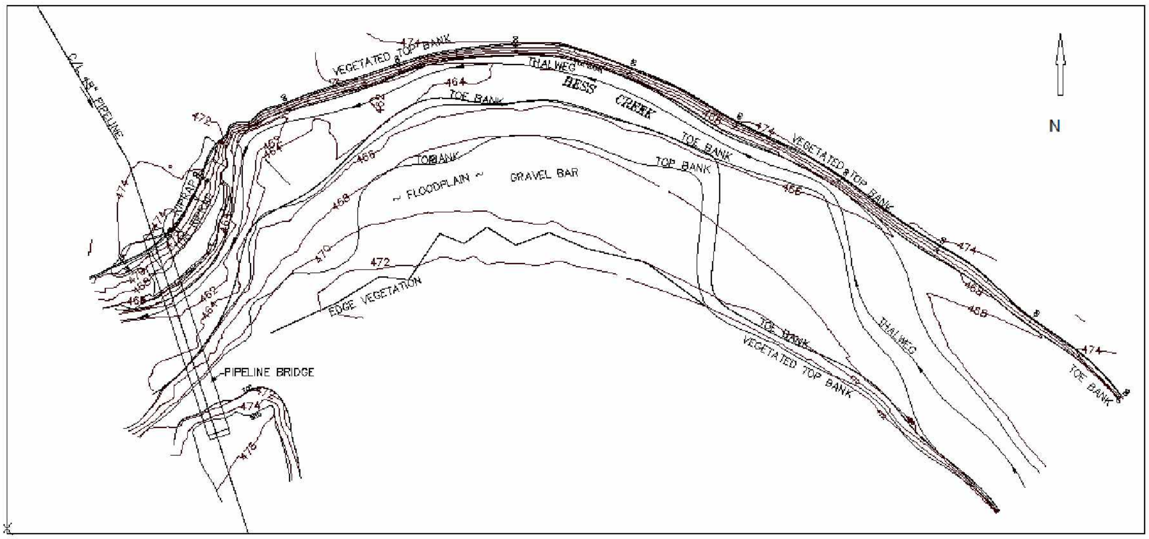

Figure 2.3 Original pre realignment topography of Hess Creek, survey by Bell Tikigaq, J.V.

After the meander was realigned and the downstream pointed re-directive vanes installed 2005 an as-built survey of the new baseline condition was performed. Annual monitoring surveys similar to those done in 2004 were performed for the next five years. Ortho-rectified and geo-referenced aerial photography were also taken pre and post construction to monitor the migration and stability of the meander. On 5 and 12 May 2010, bathymetry measurements were conducted using Teledyne RD Instruments, 1200 KHz Rio Grande acoustic doppler current profiler (ADCP), mounted on a tethered boat. Real Time Kinematic (RTK) technology was used for geographic positioning through a satellite base station and a receiver mounted on the ADCP. A total of sixteen transects were taken along the realignment as shown in Fig. 2.4. The ADCP measurement on 5 May had flows sufficiently high to submerge the vanes and those on 12 May were lower flows and none of the vanes were submerged. On the same dates water surface elevations were measured directly with a hand held rod mounted with a geographical positioning receiver. Elevations were taken on all sixteen cross sections on the outer and inner banks of the study reach to obtain transverse and longitudinal water surface slopes. To reduce errors and for quality assurance transects made with the ADCP with flows rates that deviated more than 5% from prevalent measured flows were not included in the analysis.

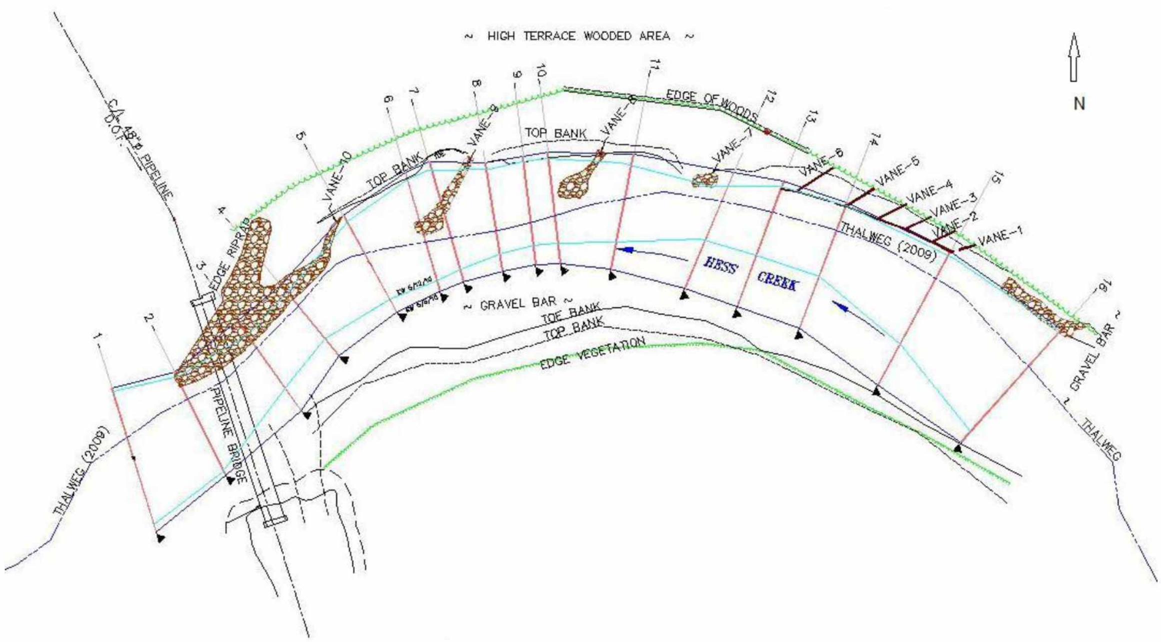

Figure 2.4 Realigned channel and location of acoustic doppler transects

2.3 Hess Creek Geomorphology and Design of Hydraulic Structures

Hess Creek is a tributary of the Yukon River. The study area is located in a subarctic boreal forest environment underlain with discontinuous permafrost. A floodplain soil profile consists of an organic layer, followed by silts, then alluvial gravels and sands down to bedrock. The point bar material consists of sandy gravels with a d_{50} of 3.8 cm.

At the pipeline crossing the creek has a torturous meander pattern with numerous oxbows on reaches upstream and downstream of the bridge. In a span of four decades from pipeline route selections in the 1960's or earlier to 1980's two meanders were cut-off. One located upstream and another downstream of the bridge that was installed in 1977. These cut-offs altered the stream gradient in the vicinity of the crossing resulting in increased bank erosion. The first cutoff was fully developed in the early 1970's (HDR Engineering 1992). It was 625 m upstream of the bridge and reduced the meander length from 1825 m to 300 m. Cause of the cutoff is not known but may be due to lateral stream migration in ice rich soils and not precipitated by a major flood. The second cutoff was 375 m downstream of the pipeline bridge that became fully developed by the 1980's. The meander length was reduced from 470 m to 335 m likely due to a series of high flood events from 1975 to 1978. In ice rich soils hydraulic and thermal erosion is accelerated whenever the soils are exposed, a process of lateral stream migration in permafrost environments that is well documented (e.g. Brown and Kreig 1983). Therefore from planning, design and installation of the bridge crossing the reach most likely was already in a state of disequilibrium however subtle the signs may have been (Fig. 2.1).

At the pipeline crossing the creek is 40 m wide and the pipeline is supported by a 55 m single span steel plate girder bridge. The drainage basin is 1310 km^2 and the bankfull discharge is 96 m^3/s based on a flood frequency analysis from a USGS gauged station approximately 3.5 km downstream of the study area. The eroding meander bend upstream of the bridge had a 98 m radius of curvature and it was transformed to a radius of 178 m. The channel was realigned laterally towards the south (inner bank), gradually from 0 m at the upstream end to 22 m at the downstream end just before the bridge abutments (Fig. 2.4). Material excavated from the new channel was used to infill the old channel on the outer bank. The material filled space between the vanes and created a functional floodplain. Fig. 2.5 is a typical section view of the new channel at cross section 7 and vane 9. Total length of the realignment is 243 m consisting of ten downstream pointed guidevanes and a transition structure on the upstream end (Fig. 2.4). The transition piece is keyed into the bank. It is located in a stable reach near the upstream meander crossover and initiates flow manipulation through the new meander curvature. Based on reference reach surveys upstream and downstream of the work site, the bankfull channel width of the new channel was set at 25 m.

The vane design concept is based on an approach applied by the Rural Water Commission of Victoria in Australia (Standing Committee on Rivers and Catchments 1991). The design relied on a visual estimation of the critical line of attack on the outside streambank of the meander during flood stage. Detailed planimetric drawings, based on topographic surveys, and aerial photographs were used to estimate the critical line of attack and to position, through an iterative process the location of the deflector vanes. The guidelines followed during the design stage were that: (1) the radius of curvature for the eroding meander bend would be realigned with the bridge orientation, (2) the new channel design width and meander radius would mimic stable channel and meander radii upstream and downstream of the project site, (3) each deflector vane would be spaced so the flow passing around and downstream from the riverward end of the vane intersected the next vane and not the eroding bank, and (4) vanes would be angled approximately 10° downstream of the perpendicular to the estimated critical line of attack. Spacing and length of the vanes increased from upstream to downstream in the meander bend. Vane spacing and length were dependent on the estimated critical line of attack and the existing and proposed radius of curvatures for the meander bend. The tops of the vanes were generally level with bankfull elevation along much of their length, see Fig. 2.6 with a gradual slope at the landward end to the top of the shallow streambank. Height of the vanes was approximately 1.2 m above the new channel thalweg. The length of each vane varies from 30 m at the downstream end to 3 m near the upstream transition. At the tip of each structure is a short guidebank similar to a hockey stick blade. It guides the flow along the bend and has sufficient riprap to launch onto a scour hole (Lai and Gaboury 2008).

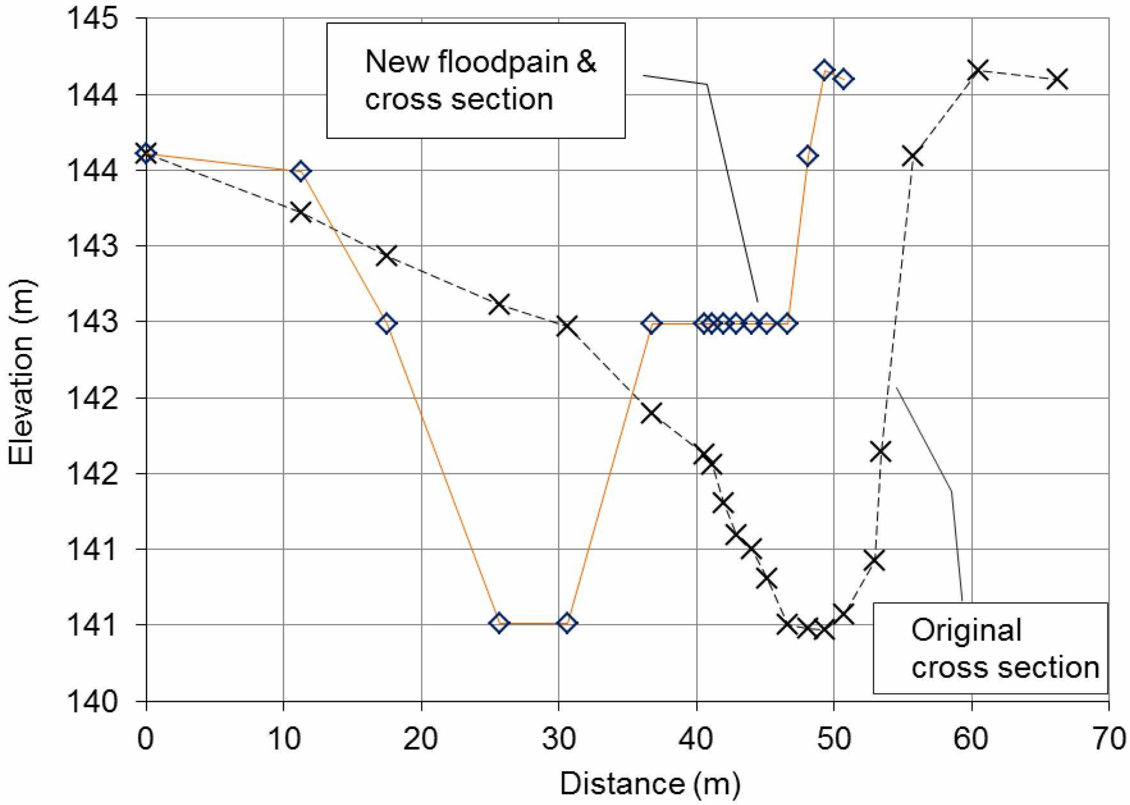

Figure 2.5 Typical realignment design cross section

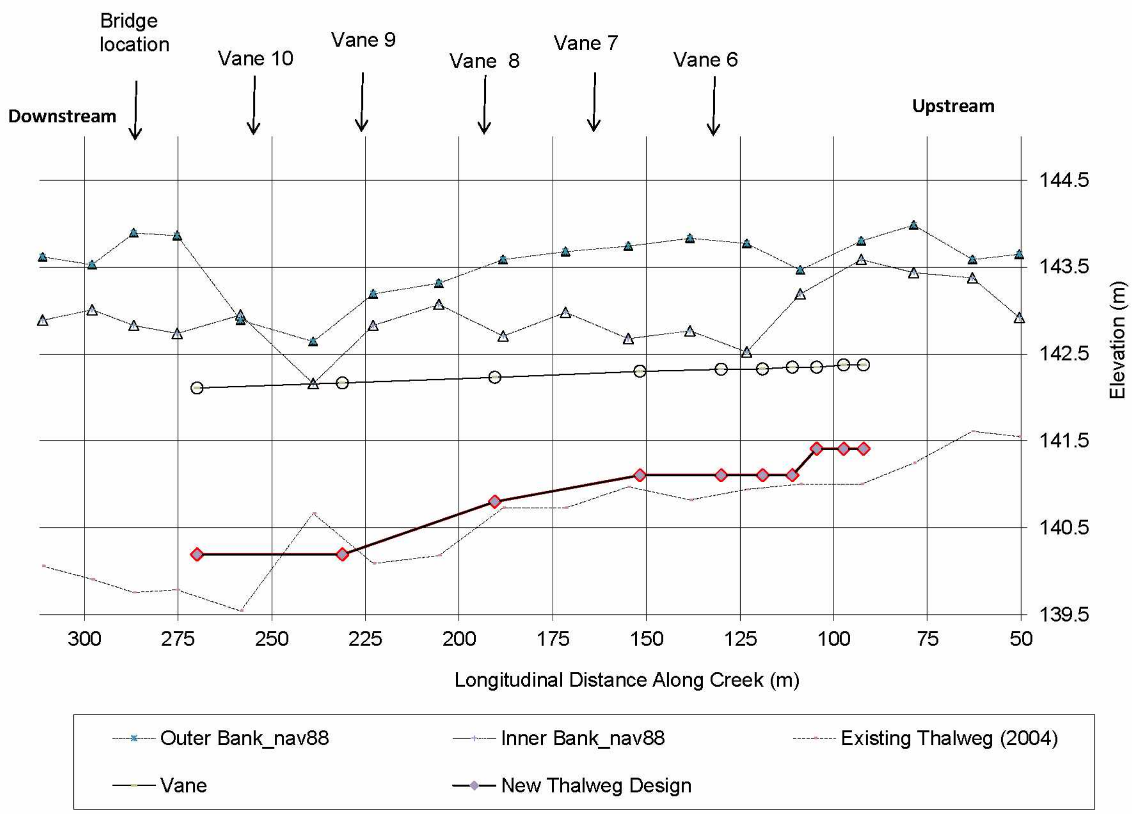

Figure 2.6 Design and existing longitudinal profiles of banks, vanes, and thalwegs

2.4 Results

In this section results pertaining to bedform, erosion and deposition, flow patterns and velocities, and hydraulic parameters and energy dissipation are presented.

2.4.1 Bedform

After five years the post vane thalweg depth at the monitored cross sections did not vary by more than 0.3 m. The erodible bed attained its current condition within a year. This would indicate that the streambed had reached a state of dynamic equilibrium. The bedform had a significant transformation between pre and post installation of the vanes. With its natural eroding bank the original meander bend bed profile consisted mainly of a gentle sloping pool with the deepest section near the apex of the curve (Fig. 2.3). Because of rock armor placed to protect the bridge abutment a decade earlier the meander pattern was slightly altered. However the reach still exhibited a typical pool profile of a natural eroding meander (Leopold et al., 1964). After installation of the redirective vanes the meander bed morphology exhibited a form similar to a pool-riffle series. Several short deep pools formed adjacent to the downstream tip of each protruding vanes as shown in Fig. 2.7. The pools are oriented parallel to the main flow with its longitudinal axis defining the stream thalweg.

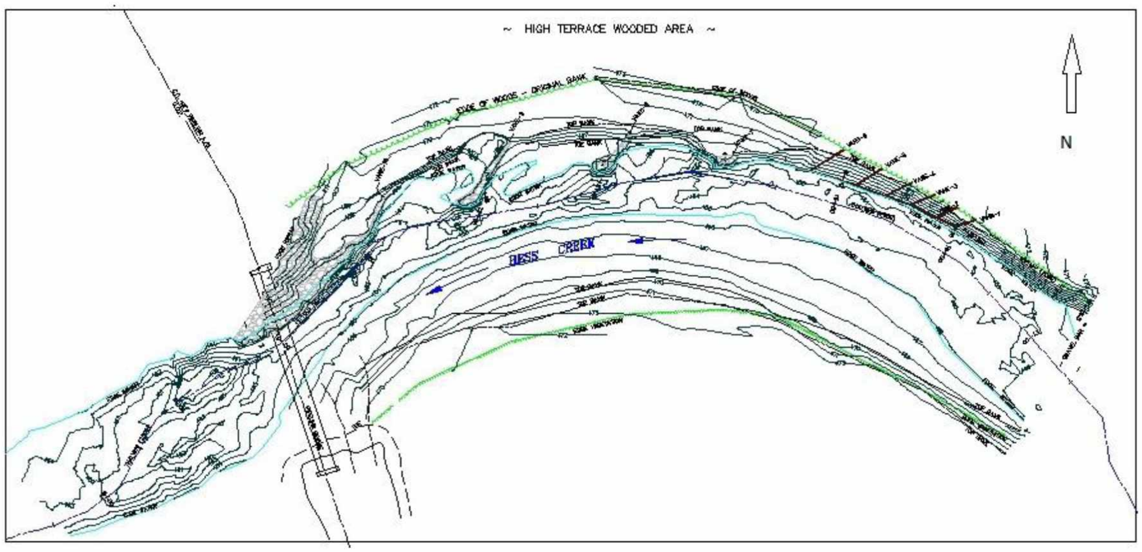

Figure 2.7 Vane Locations and 2009 Post Realignment Topograpy, survey by Bell Tikigaq, J.V.

It can be deduced from this bedform that the normal spiral flow pattern attributed to secondary currents on the outside bank of a natural meander bend is severely altered from flow hydraulics imposed by the vanes. The bed longitudinal slope for the study reach also became slightly shallower after installation of the vanes (Figure 2.8).

2.4.2 Erosion and Deposition

The maximum scour or thalweg depth with the redirective vane alignment is essentially the same as the initial reference condition prior to vane installation. There is less than 0.3 m difference between them, with the vane design having a slightly deeper scour hole. However, the scour location and pattern was different as explained in the previous section. The downstream pointed redirective vanes did not alter the erosive power of the stream but displaced it to another location. In this study scour was displaced to the tip of the protruding vanes by shifting the main flow away from the toe of outer bank. Fig. 2.8 shows the longitudinal profiles of the stream thalweg before and after installation of the downstream pointed vanes.

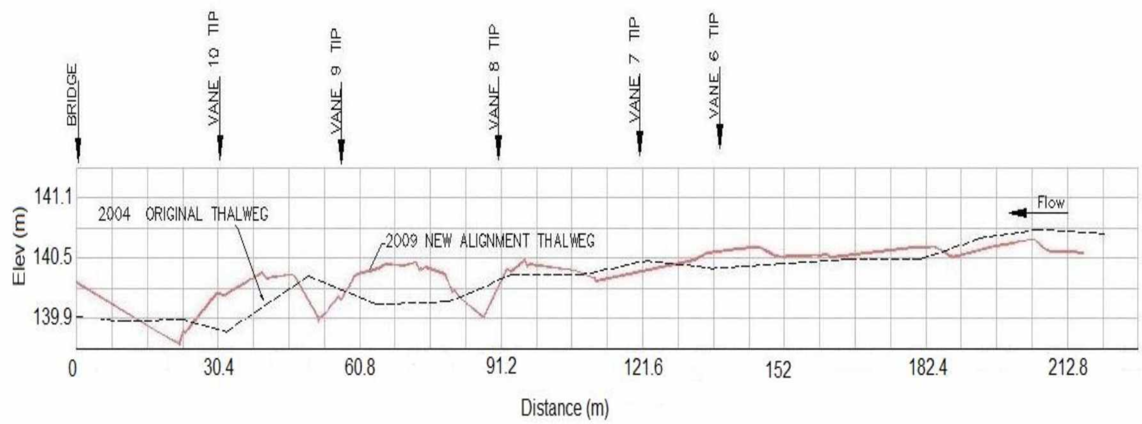

Figure 2.8 Comparison of original and post alignment longitudinal thalwegs

The vanes also altered the transverse bed slope along the bend. Figs. 2.9 and 2.10 are cross sections at the tip of vane 8 just upstream of transect 10 before and after realignment. The transverse slopes from the thalweg to the apex of the inner point bar are 5.7% for a natural eroding bank and 8.7% with redirective vanes. Channel widths when measured from bank to bank vegetation line also increase with installation of the vanes from 49 m to 61 m respectively, these results are summarized in Table 2.1.

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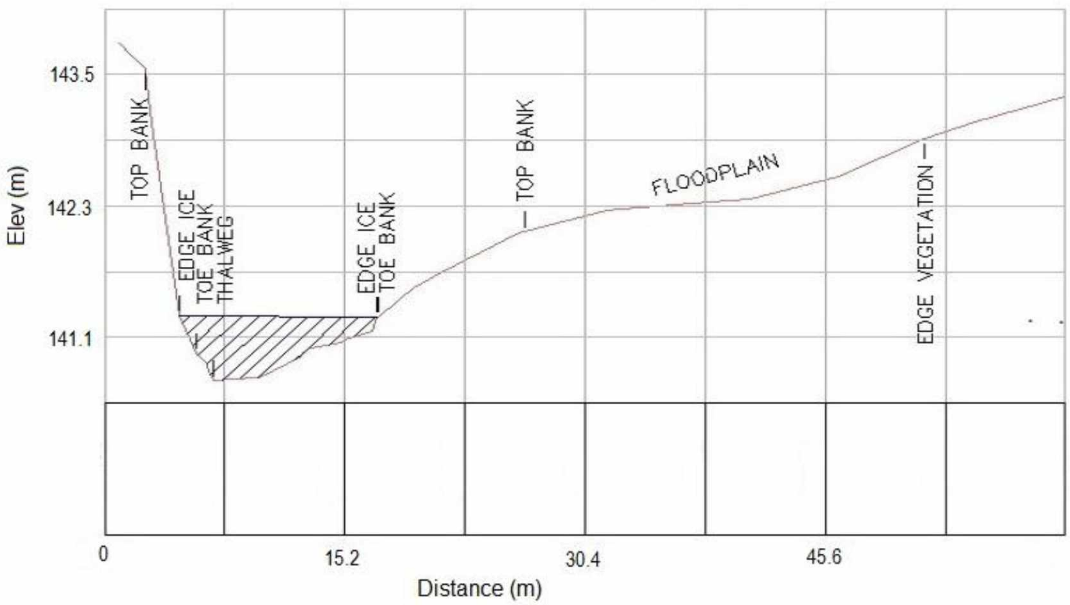


Figure 2.9 Original cross section at tip of vane 8 upstream of transect 10

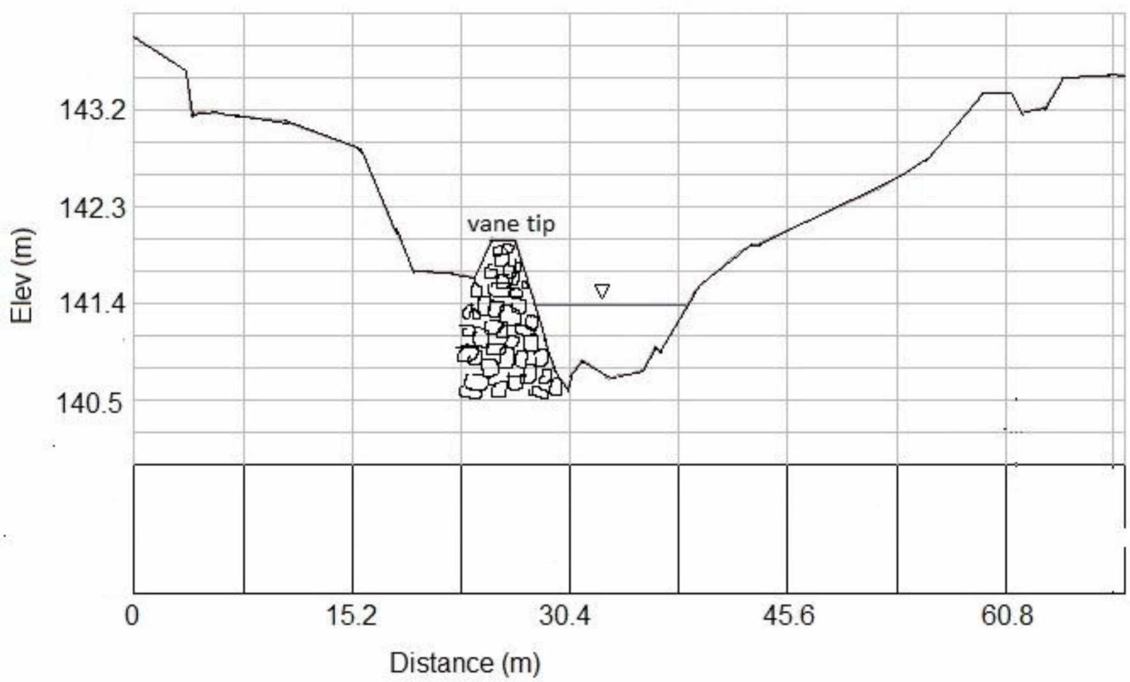


Figure 2.10 Post alignment cross section at tip of vane 8 upstream of transect 10

At Hess Creek, the vanes were designed to be overtopped. As mentioned previously the meander radius was lengthened by moving the channel laterally towards the point bar which created additional floodplain relief on the outer (concave) bank. This had the effect of stabilizing the outer bank slope by reducing it from 59% from the natural condition to 11% for post vane installation (Fig. 2.10).

2.4.3 Flow Pattern and Velocities

Installation of instream structures such as rock vanes on a meander bend significantly alters the flow pattern. As discussed previously the bedform is transformed due to local scour near the tip of the vanes. The protruding vanes create flow contractions resulting in increasing velocities followed by flow separation due to a zone of expansion in areas between vanes. These expansion areas create countercurrents or an eddy where flows circulate upstream and downstream. However, unlike conventional spur dikes the low profile vanes with sloping crests can be overtopped at higher flows limiting the strength of the countercurrents which have been associated with excessive siltation and/or erosion.

Fig. 2.11 is an idealized typical transverse flow circulation pattern (Markham and Thorne 1992) of a cross section on a natural meander bend and Fig. 2.12 is the flow pattern for transect 9, just downstream of vane number 8 for a high flow condition. Fig. 2.13 is the transverse velocity vector field measured with the ADCP for the high (submerged vanes) flow conditions.

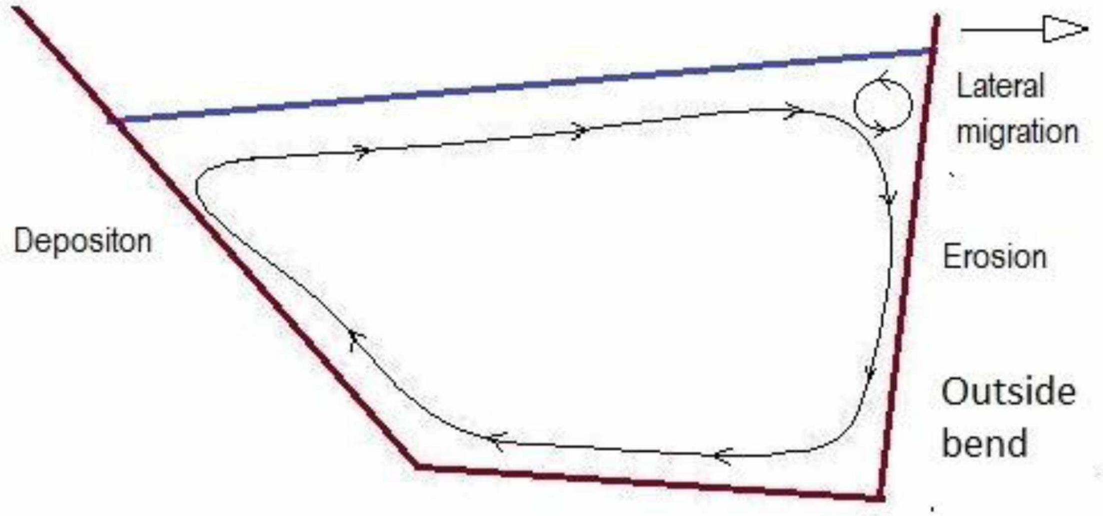


Figure 2.11 Typical secondary circulation flow pattern on a natural meander bend

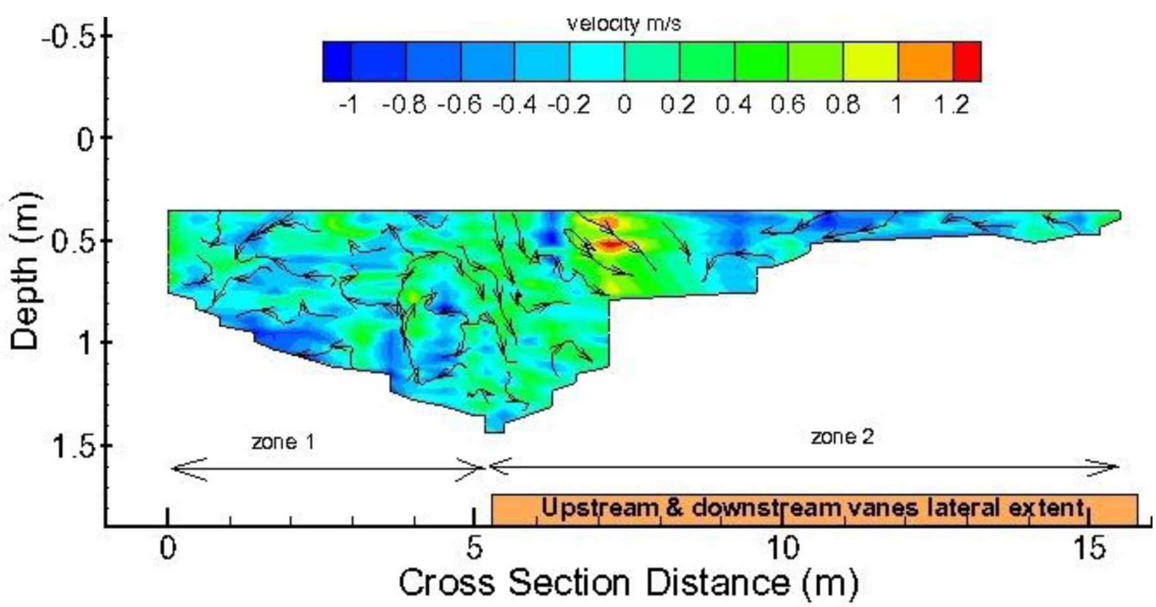


Figure 2.12 Submerged vane transverse streamlines and velocity contours at transect 9 positive value is towards outer bank (right)

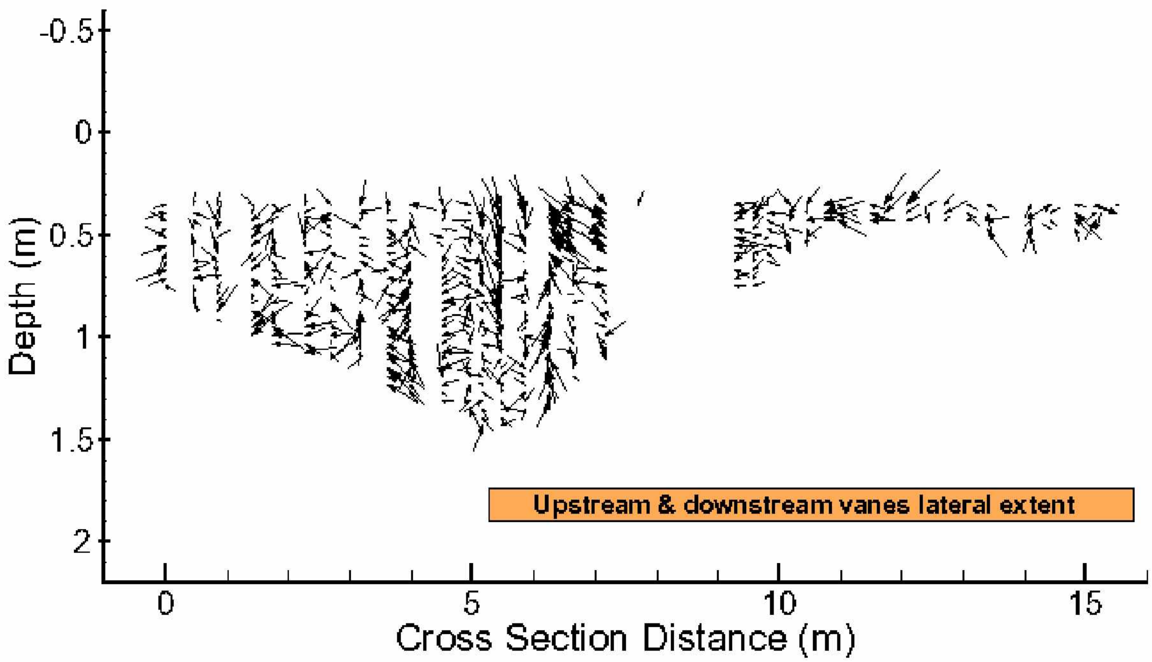


Figure 2.13 Submerged vane transverse velocity vectors at transect 9

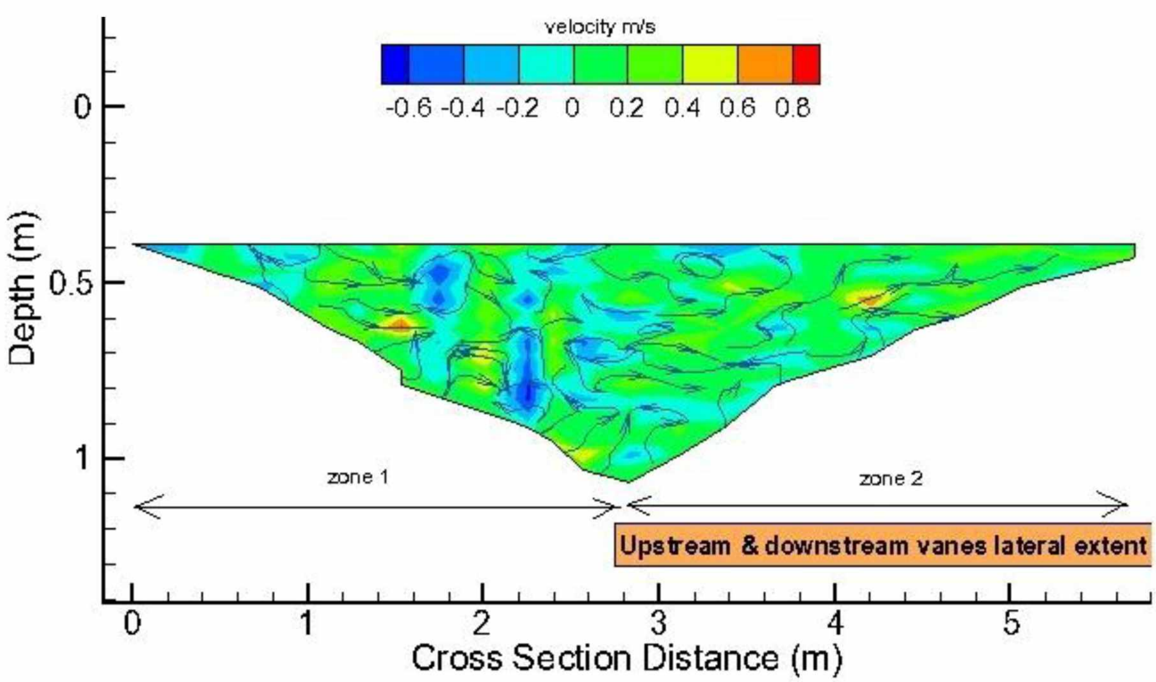
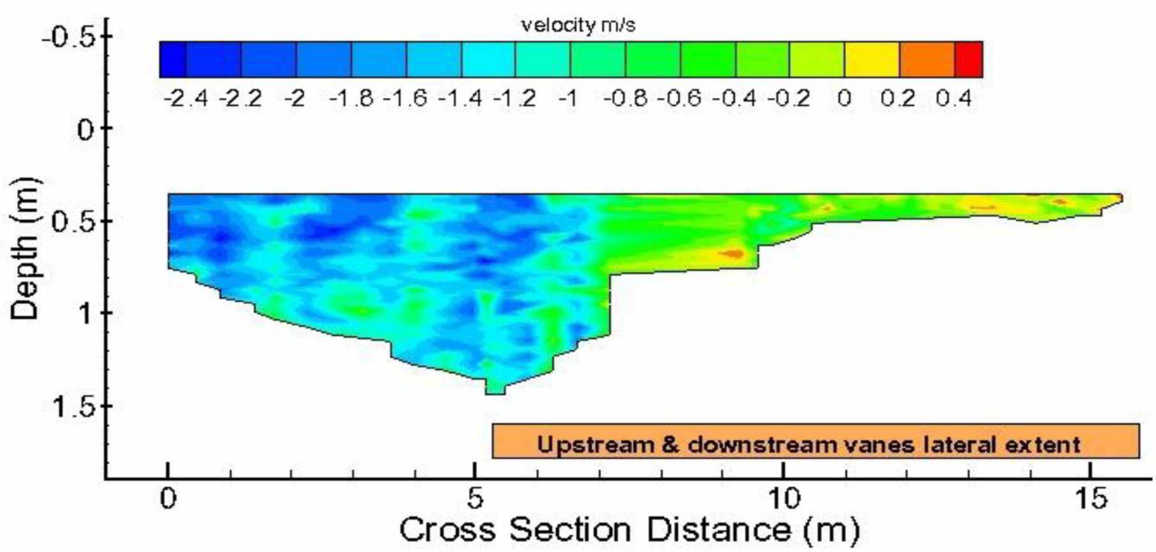


Figure 2.14 Exposed vane transverse streamlines and velocity contours at transect 9 positive value is towards outer bank (right)

The natural meander bend consists of a single dominant counterclockwise circulating cell when looking downstream. But with the vanes the transverse flow patterns consist of multiple circulation cells and shear layers. These circulation cells are generally in two zones: zone (1) from the thalweg or near the vane tip where cells circulate on the main channel towards the inner bank, and zone (2) from the thalweg where cells circulate towards the outer bank, (see Figs. 2.12 and 2.14). When the vane is submerged there is a dominant transverse circulation cell present in zone (1). However, the highest transverse velocities are near the surface in zone (2), (see Figs. 2.12 and 2.13). When the vanes are exposed the opposite occurs. The transverse circulation cells are smaller and more fragmented but the velocity magnitudes are more concentrated in zone (1) as shown in Fig. 2.14.

In Figs. 2.15 and 2.16 are streamwise (longitudinal) velocity contours for high and low flow conditions. These contours demonstrated that the existence of upstream circulating eddy is less when the vane is submerged than at low flows. For example when the vane is exposed the upstream circulating eddy occupy over half of zone 2 cross section (Fig. 2.16) when compared to the submerged condition (Fig. 2.15).



Figures 2.15 Submerged vane streamwise velocity contours at transect 9 positive value is upstream direction

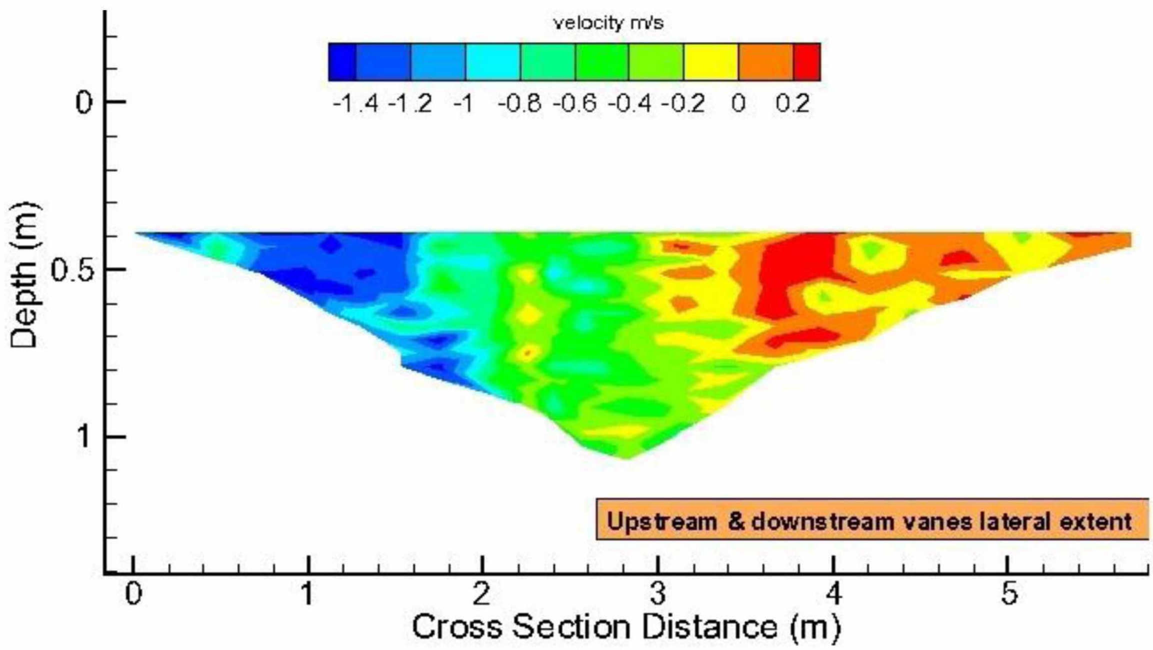


Figure 2.16 Exposed vane streamwise velocity contours at transect 9 positive value is upstream direction

Two vertical circulating shear layers are prominent in the submerged vane condition. The vertical shear layers are centered along the thalweg one in the main channel, zone (1) and another towards the outer bank, zone (2). Highest velocities are found just on the inside edge of the thalweg at a depth one quarter and one half the distance from the surface (Fig. 2.17).

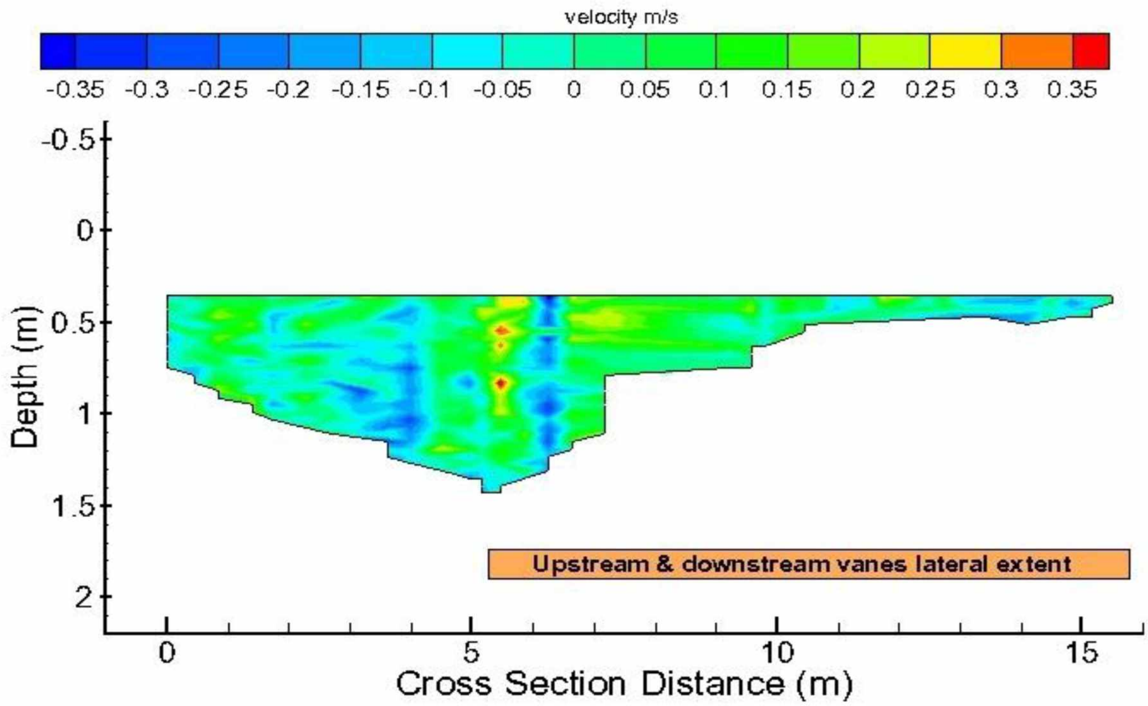


Figure 2.17 Submerged vane vertical velocity contours at transect 9 positive value is downwards

In the low flow condition the vertical shear layers are less uniform and weaker. One dominant vertical shear layer is located on the main channel side of the thalweg, zone (1). The highest velocity is found near the surface located horizontally half way between the thalweg and the outer bank, zone (2) which is an expansion area between vanes (Fig. 2.18).

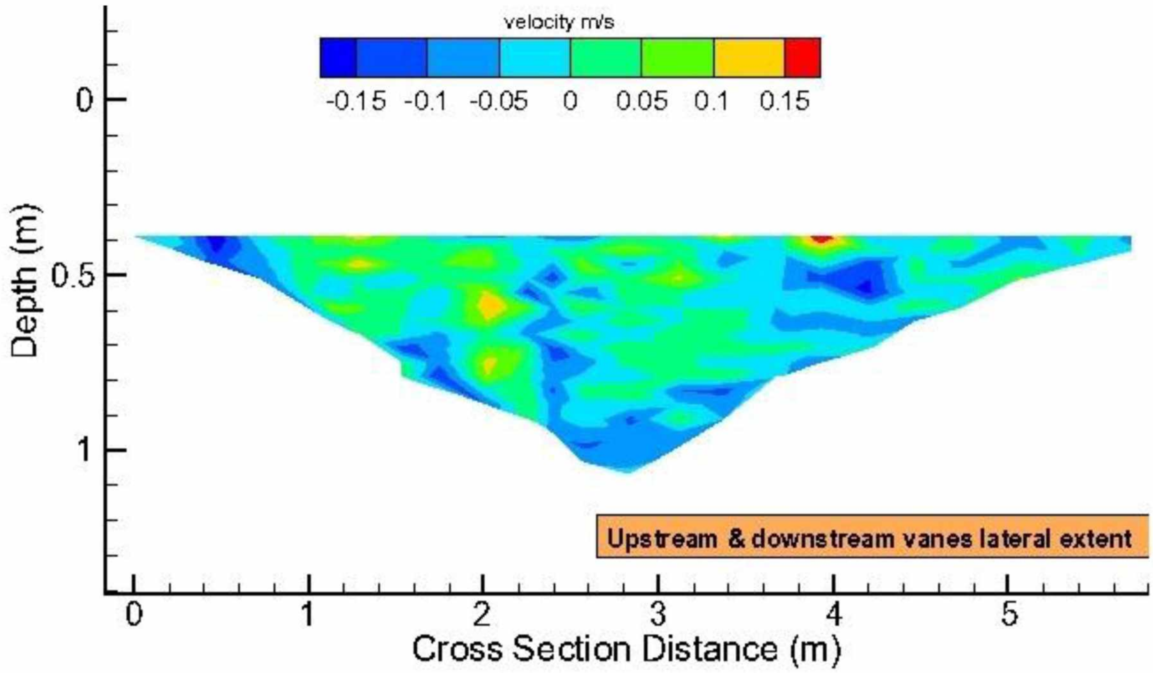


Figure 2.18 Exposed vane vertical velocity contours at transect 9 positive value is downwards

2.4.4 Hydraulic Parameters and Energy Dissipation

Superelevation or transverse water surface slopes along a meander bend have an integral role in development of scour due to transverse currents. Fig. 2.19 displays transverse slopes for high and low flow conditions. Also displayed in the figure is the longitudinal slope at high flow. The transverse slopes were derived from direct measurements by subtracting the difference in outer and inner bank elevations and dividing the distance between the measured locations. The slopes increase at transect 11 shortly after entering the meander just upstream of the apex. Slopes decrease downstream at transect 9 in an expansion area between vanes. Then it is followed by a second peak near the apex at transects 7 and 8, where the longitudinal slope is highest just before a localized crossover flow at transect 6.

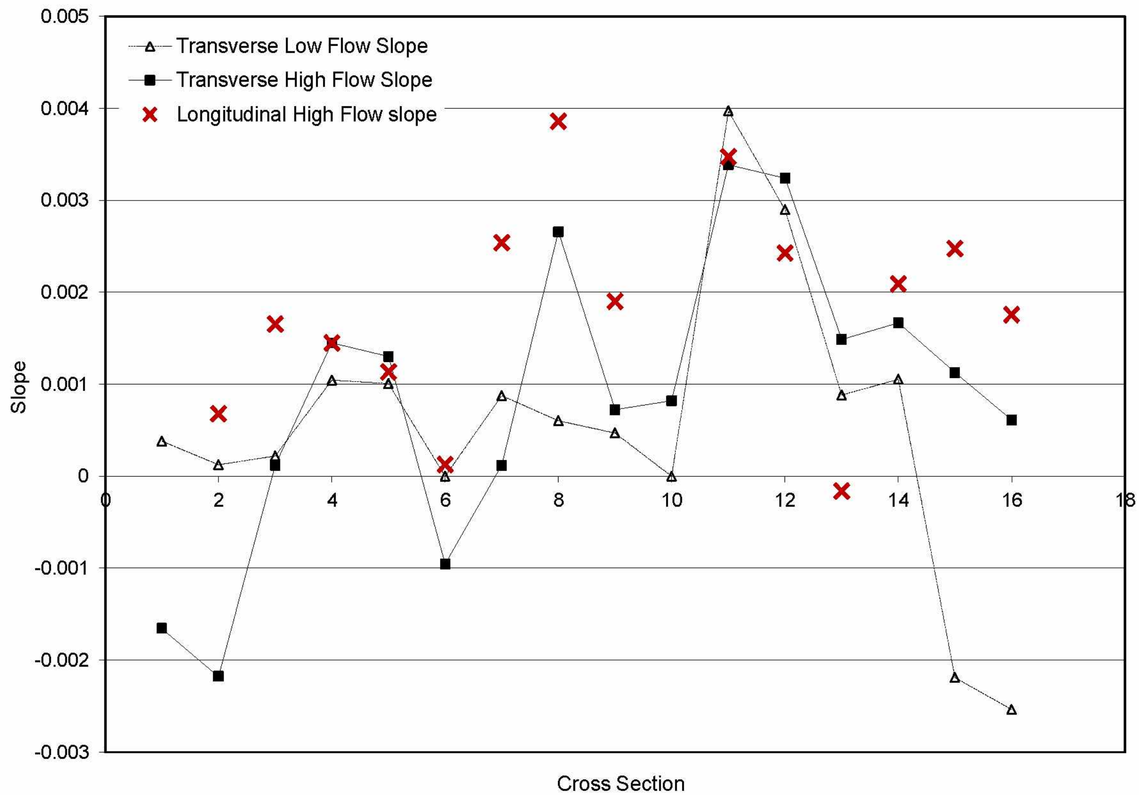


Figure 2.19 Transverse and longitudinal surface water slopes along realigned meander; transverse slopes positive value is superelevation on outside bend (north)

In curved channels the energy expenditures are mainly due to: 1) Internal fluid friction from transverse flows, 2) Boundary resistance from transverse shear, 3) Eddy losses from flow separation, and 4) Eddy losses from surface fluctuations at high Froude numbers (Chow 1959, Chang 1988). This results in greater energy expenditure when compared to straight reaches. Rozovskii (1957) provided analysis of energy expenditure for fully developed flow with

$$S'' = \left(\frac{12g^{\frac{1}{2}}}{C} + \frac{30g}{C^3}\right)\left(\frac{D}{r_c}\right)\boldsymbol{F}^2 \tag{1}$$

where S" is the transverse energy gradient, g is the gravitational acceleration, C is Chezy's coefficient, D is the depth of flow, r_c is the center radius of curvature, , and **F** is the Froude number. The above equation indicates that the transverse energy gradient increases with channel roughness along with other variables such as flow depth. Figs. 2.19 and 2.20 generally validate this assumption in regards to channel roughness. In Fig. 2.19 the highest transverse slopes are at cross sections 8, 7, and 12 which are at or upstream of the meander apex. Fig. 2.20 shows Manning's roughness along the meander curve with the three highest average values at cross sections 8, 9, and 11.

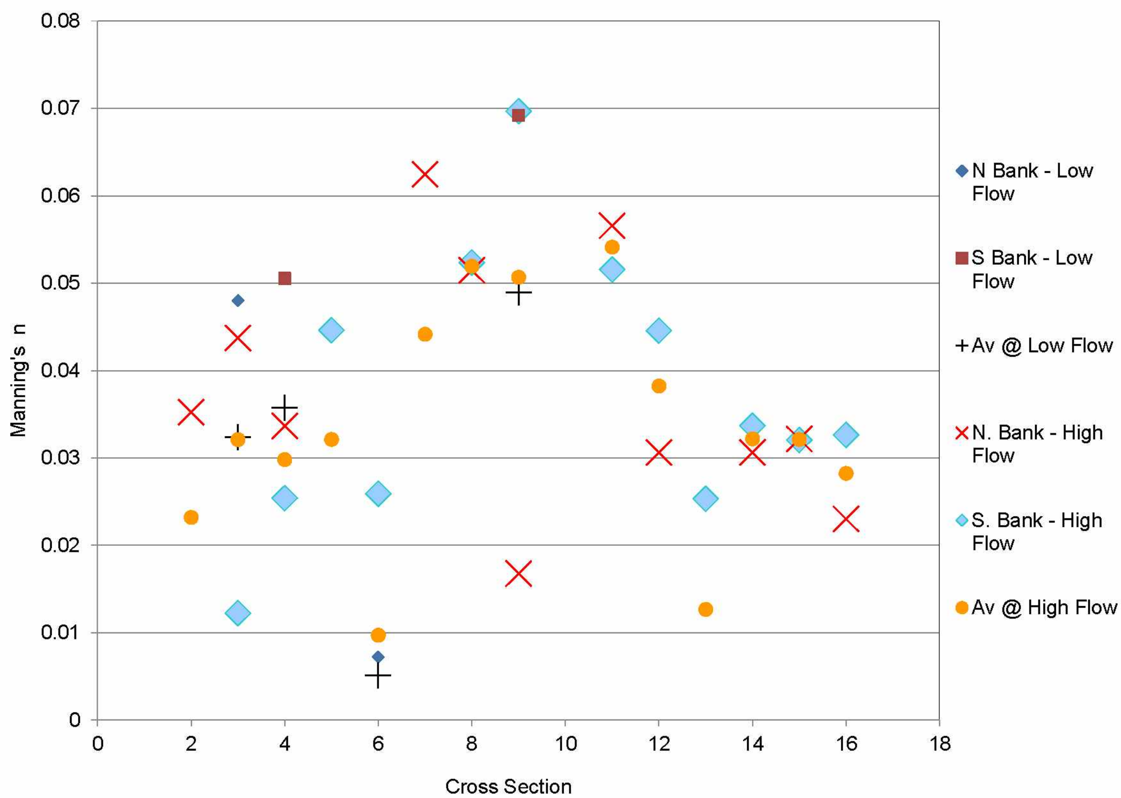


Figure 2.20 Manning's coefficient along realigned meander bend

Values of Manning's n on Fig. 2.20 were derived from the following equation

$$n = \frac{\left(R^{\frac{2}{3}}\right)\left(S'^{\left(\frac{1}{2}\right)}\right)}{U} \quad (2)$$

where R is the hydraulic radius S' is the longitudinal energy gradient, and U is the depth averaged velocity. Hydraulic radius and averaged velocity were calculated using VMS software (Dongsu et al. 2009). Rozovskii's equation was modified by Chang (1983) with the following

$$P = \gamma QS \quad (3)$$

$$P' = \gamma QS' \quad (4)$$

$$P'' = yQS'' = yQ\left\{\frac{2.07f + 4.6f^{\frac{1}{3}} - 1.83f^{\frac{3}{2}}}{0.565 + f^{\frac{1}{2}}}\right\}\left(\frac{D}{r_c}\right) \quad (5)$$

$$P = P' + P'' = yQS = yQ\left(\frac{f}{8}\right)\boldsymbol{F}^2 \quad (6)$$

where P is the rate of energy loss per unit channel length, P' is longitudinal rate of energy loss, P" is the rate of energy loss associated with the transverse flows, y is specific weight of fluid, Q is the flowrate, S is the total energy gradient, and f is the friction factor. Equation 6 indicates that total energy losses in a curve are directly related to channel roughness and Froude number which is

$$\boldsymbol{F} = \frac{U}{\sqrt{gD}} \quad (7)$$

Fig. 2.21 is a plot of the energy losses along the stream curve using equation 6. The highest energy losses are in transects 8 to 11 and it corresponds well with the values of Manning's n shown on Fig. 2.20.

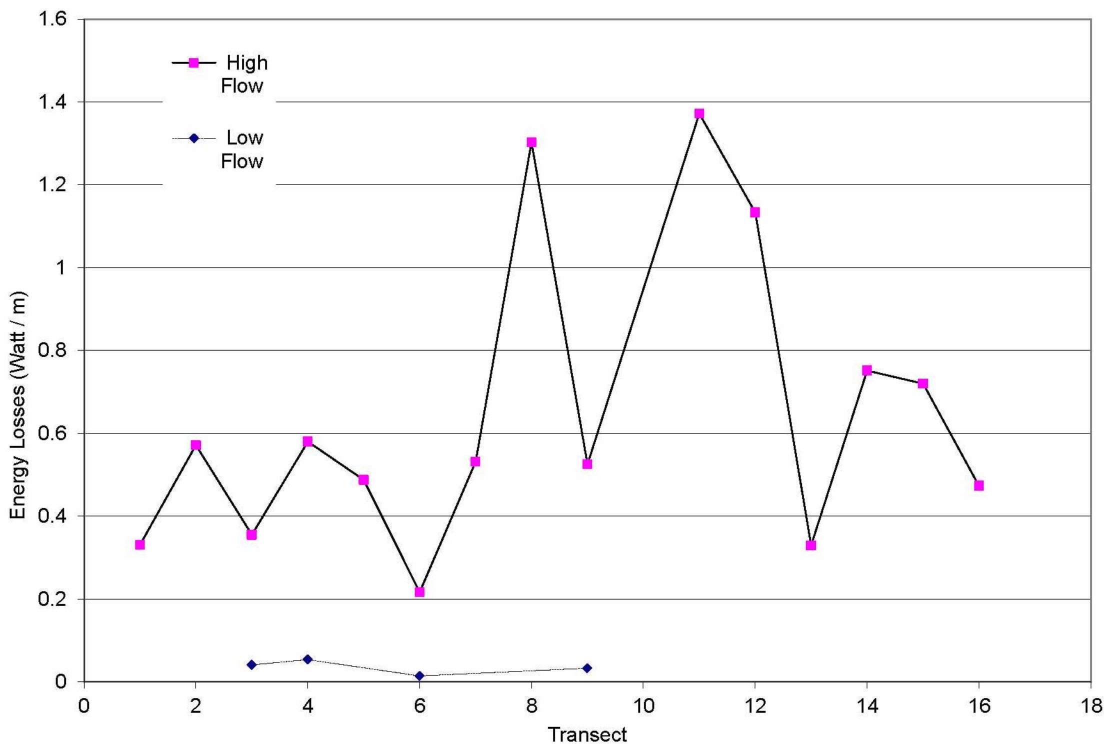


Figure 2.21 Energy losses at transects along realigned meander

Chang's equation 5 predicts that the highest rate of energy losses due to transverse flows, P", on a curved channel occurs where the stream has the lowest roughness – in addition to other variables such as radius of curvature and flow depth. In Fig. 2.20 the lowest roughness along the meander bend is at cross sections 6 and 13. This corresponds to the same cross sections where the highest ratios of transverse energy to total energy loss rates, P" / P, are found (Fig. 2.22). The figure also shows that the highest ratio or contribution to transverse energy expenditure is not at the apex of the curve but upstream on cross section 13, and downstream on cross section 6. This coincides with locations along the channel where total energy losses along the meander bend are lowest (Fig. 2.21) which is where the longitudinal energy slopes are also lowest.

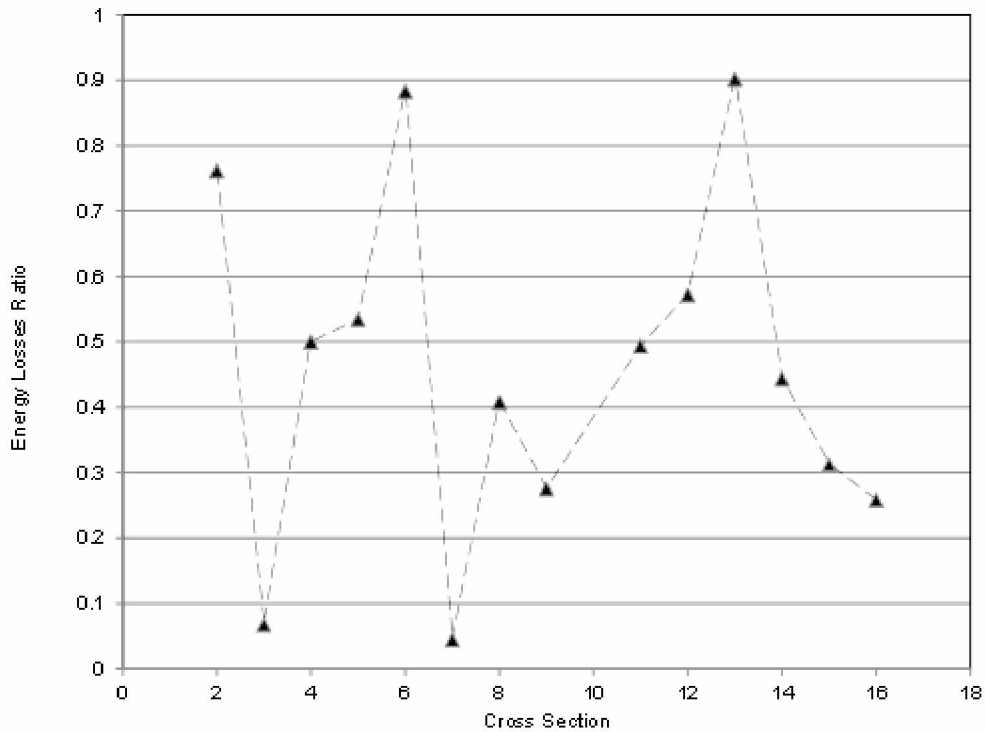


Figure 2.22 Ratio of Transverse to total energy losses at high flow for transects along realigned meander

2.5 Discussion and Application

2.5.1 Discussion of Results

2.5.1.1 Geomorphic Features

Change in bedform from a pool along the natural meander bend to a pool-riffles series demonstrates the influence of the vanes on channel hydraulics. Although the reach was straightened by altering the original radius of curvature from 98 to 178 meters the longitudinal bed slope decreased by half from 0.8% to 0.4% post realignment (Fig. 2.8). This would appear counter intuitive since the meander length was shortened by a 55% increase in radius of curvature. However it is indicative of greater energy expenditure through the reach due to the following factors: increased roughness from the vanes, expansion and contraction losses of energy along vanes resulting in local scour and deposition, and greater cross section flow areas through the new floodplain (Figs. 9 and 10). The functional floodplain installed on the outer bank likely increased flood attenuation resulting in slower velocities and greater deposition of bed material.

Table 2.1 Geomorphic features pre and post realignment

	Original Meander	Realigned Meander
Radius of Curvature (m)	98	178
Longitudinal Bed Slope (%)	0.8	0.4
[a]Transverse Bed Slope (%)	8.7	5.2
[a]Outside Bend Slope (%)	56.6	11
[a]Active Floodplain Width (m)	49	61

[a]Taken at cross section 6

The maximum scour depth in the reach remained approximately the same between pre and post alignment (Fig. 2.8). The structures relocated the scour location from toe of outer bank to the vane tips. This field measurement is in agreement with laboratory experiments reported by Bhuiyan et al. (2010) for upstream pointed vanes. It is not well understood why the scour depths remained relatively unchanged. Quantifying scour depths especially local scour is still an evolving field and many factors such as angle of attack, local velocities and energy slopes, structure geometry and orientation, turbulence, etc. can influence the local scour depth. However, the author has the following postulate that could help explain the phenomena: realignment changed two prominent hydraulic variables, roughness and energy slope. The roughness increase resulted in increased total energy losses per unit length along the meander (eq. 6). The vanes also added additional losses due to contraction and expansion areas. But the decrease in energy slope to half the pre-aligned value means that the stream power also decreased by half. This is because stream power is proportional to the product of unit flow area and energy slope. All other parameters being equal such as flow rate, substrate material, energy slopes at upstream and downstream reaches of the study area, means that the available energy at the upstream end of the study area remained unchanged. Therefore it is plausible that the diffusion of stream power at the study reach was compensated by increased energy expenditure due to higher roughness, expansion and contraction losses, etc. Furthermore, it could be that the additional floodplain and radius of curvature provided by the realignment were insufficient to alter the erosive capacity of water at higher flows.

2.5.1.2 Channel Hydraulics and Transverse Flows

In a curved channel spiral or transverse flows are generated due to: 1) centripetal force as particles are deflected from a straight path to a curvilinear geometry, 2) superelevation on the outside bend that affects the vertical velocity distribution, 3) wall friction that favor higher velocities near the center of the channel than the channel walls (Chow 1959). Channel lateral migration is chiefly attributed to transverse flows that scour the outer bank and deposit the sediment on the inner side of the curve due to counterclockwise flows when looking downstream, see Fig. 2.11. Rozovskii (1957) provided detailed analysis of flow in curved channels. His analysis of transverse flows compared well with laboratory measurements but not so well on field measurements with irregular cross sections (Chang 1988). Hess Creek post realignment is an example were the cross sections are irregular instead of rectangular. The flows are more diverse and complex when compared to a natural meander. This is due to the complexity added by the vanes in terms of eddy currents, multiple shear layers from smaller secondary flow cells and large variation in flow pattern and velocities. These variations are likely caused by an exchange is momentum between the main channel and expansion areas between the vanes.

With instream rock vanes the spiral flow pattern typical of naturally eroding channel bends is disrupted (Figs. 2.12 – 2.14) with the presence of more heterogeneous patterns. The large dominant circulating cell on a natural meander bend is fragmented into smaller circulation cells. However at high flows were vanes are submerged a resemblance to the dominant circulating cell is still discernible on the main channel near the tip of the vane (Fig. 2.12). This large circulating cell is the cause of local scour holes on the vane tips (Figs. 2.7 and 2.8). When the vanes are submerged the recirculating eddy is very weak, almost non-existing (Fig 2.15). The field measurements are in general agreement with those of Yossef et al. (2011) that performed laboratory experiments on groins. That is when structures are submerged momentum transfer of water flowing over the vanes hinder horizontal recirculation due to expansion zones. But at low flows when vanes are exposed upstream eddy currents cover over half the cross section in the expansion area between vanes (Fig. 2.16). There is a large difference in maximum velocities attained between upstream eddy currents and downstream main channel flows. The upstream recirculating eddy velocity is about 14% of the main channel. Although the eddy current is relatively weak compared to the main channel flow they have a significant influence on stream morphology and biological function. The eddy currents result in sediment deposition on the active floodplain, provide flow diversity, and enhance flora and fauna such as resting areas for fish and growth of wetland vegetation (Bhuiyan et. al. 2010, Lai and Gaboury 2008).

2.5.2 Effectiveness and Applicability of Design

One could argue that six years is not a sufficient time span to make a definitive assessment on the effectiveness of downstream pointed rock vanes to realign a meander bend. However, the peak streamflow the reach experienced since realignment equates to a ten year return period (Curran et. al 2003). This short time did provide adequate monitoring data to conclude that thus far the design concept has been generally effective at achieving its main objectives – to realign the meander bend, minimize erosion of the outer bank, and reduce likelihood of an avulsion upstream of the bridge. Since realignment erosion of the original outer bank (Figs. 2.2 and 2.3) has completely stopped. But because the vanes are designed to be overtopped at higher flows to achieve a functional floodplain these events also resulted in erosion of fill placed between vanes. The lower reach between vanes 7 and 10 (Fig. 2.7) lost fill material placed to build the floodplain due to erosion. Although the fill erosion does not structurally compromise the design it did hinder vegetation rooting and its growth on the affected areas. Because newly built floodplains are mostly bare of vegetation they are most vulnerable during the years prior to their rooting. An effective way to minimize erosion used on other projects is to increase floodplain roughness with addition of woody material. The woody materials promote deposition of fine sediments and seeds. Wood can also be placed on top of vanes to raise their elevation and reduce frequency of overtopping while maintaining a semi permeable layer. This can have economic and ecological benefits by reducing the volume of riprap and providing and additional carbon source to the stream.

Use of downstream pointed rock vanes to realign meander bends would be most applicable on reaches with shallow slopes such as single channel meandering streams where the angle of attack is more predictable. On braided streams this approach may be possible depending on local conditions. For example a well channelized subchannel may be appropriate but adequate spacing of the vanes would be critical to protect against changes in angle of attack. This approach would be similar to the use of traditional spur dikes where closer dike spacing is required. However, the advantage of rock vanes is that they can be overtopped and still remain functional. This is an important factor because spur dikes must be designed not to be overtopped for the design life of the structure or they will fail. But certain local conditions such as aufeis formation and ice jams are difficult to estimate maximum flood stage. In fact the maximum local flood elevation due to aufeis and ice jams can exceed the probable maximum design flood due to precipitation. The choice of whether to use rock vanes, or other traditional structures such as spur dikes would depend on site conditions, economics, and stakeholder needs. In the case of Hess Creek the rock vanes resulted in an economical solution because less rock was required than a traditional structure (Lai and Gaboury 2008)

However if downstream pointed rock vanes is the chosen design, stakeholder education and endorsement are critical for its overall success and acceptance. The design concept applied at Hess Creek aims at maximizing stream mobility without compromising integrity of the pipeline bridge. Therefore, a restored reach using this concept will not necessarily have the idyllic image people are cultured to seeing, such as a meandering stream with symmetrical dimensions and smooth grassy banks. Instead, depending on details of the final design a more likely image is of woody debris deposition and wetland vegetation on the floodplain, an irregular and dynamic bank, exposed rock vanes interspersed with vegetation and woody material, and backwater or eddy flows on embayment areas between vane structures. These embayment areas on the floodplain can be enhance with placement of woody material (anchored) to increase roughness and enhance biological function (Abbe et al. 2003). However when compared to a traditional design the final product will likely have a more stable naturally sustainable reach with better flood attenuation, an active floodplain, less bank erosion, and more hydraulic and biological diversity.

2.6 Acknowledgements

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2.7 Notation

C = Chezy's coefficient

D = Depth of flow

f = Friction factor

F = Froude number

g = Gravitational acceleration

n = Manning's roughness coefficient

P = Rate of energy loss per unit length

P′ = Longitudinal rate of energy loss

P" = Rate of energy loss due to transverse flows

Q = Flowrate

R = Hydraulic radius

S = Total energy gradient

S' = Longitudinal energy gradient

S" = Transverse energy gradient

r_c = Radius of curvature

U = Depth averaged velocity

y = Specific weight of fluid

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Chapter 3 Conclusion

3.1 General Conclusion

Downstream pointed redirective rock vanes are an innovative design concept that can be used to realign eroding stream meander bends. Hydrodynamics and effectiveness of the design were evaluated. The conclusion is that the vane structures significantly alter and disrupt secondary current patterns found on naturally eroding meander bends. These disruptions in flow patterns cause changes in erosion, sediment deposition, and local stream hydraulics. The design concept can be an effective method to realign an eroding meander bend and minimize the risk of stream avulsion. Therefore, the objectives of this study have been met by furthering the knowledge on hydrodynamics of downstream pointed rock vanes and demonstrating the effectiveness of the design concept to realign meander bends.

3.2 Site Specific Conclusion

Use of downstream pointed redirective vanes to realign a meander bend was applied for the first time in Alaska where the Trans-Alaska Pipeline Bridge crosses Hess Creek. It is located 128 km north of Fairbanks and 48 km south of the Yukon River. After six years of monitoring the realignment has generally accomplished the design objectives which are, to realign the meander bend, minimize erosion of the outer bank, and reduce likelihood of an avulsion upstream of the bridge. Since realignment erosion of the original outer bank has completely stopped. The design is an evolution and departure from the rigid traditional river engineering philosophy of the past to one that integrates biological and ecological functions, a necessity for long term sustainability of stream restoration. Since the design concept is relatively new in the practice of river engineering and restoration, site monitoring should continue to better assess its long term success and short comings. The monitoring will provide additional data that will assist in gaining a better understanding and knowledge of the design concept.